Photovoltaic Manufacturing Technology (PVMaT) Project - Latest Results

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ABSTRACT

The Photovoltaic Manufacturing Technology (PVMaT) Project was initiated in 1990 to help the U.S. photovoltaic (PV) industry extend its world leadership role in manufacturing and commercially developing PV modules and systems. It is being conducted in several phases, staggered to support industry progress. The four most recently awarded subcontracts (Phase 2B) are now completing their first year of research. They include two subcontracts in CdTe, one on Spheral Solar™ Cells, and one on cast polysilicon. These subcontracts represent new technology additions to the PVMaT Project. Subcontracts initiated in earlier phases are nearing completion, and their progress is summarized. An additional phase of PVMaT, Phase 4A, is being initiated which will emphasize product-driven manufacturing research and development. The intention of Phase 4A is to emphasize improvement and cost reduction in the manufacture of full-system PV products. The work areas may include, but not limited to, issues such as improvement of module manufacturing processes; system and system component packaging, integration, manufacturing, and assembly; product manufacturing flexibility; and balance-of-system development with the goal of product manufacturing improvements.

INTRODUCTION

The Photovoltaic Manufacturing Technology (PVMaT) Project was initiated in 1990 to help U.S. photovoltaic (PV) industry extend its world leadership role in PV manufacturing and the commercial development of PV modules and systems. As previously described [1,2,3,4], the PVMaT Project is a government/industry research and development (R&D) partnership between the U.S. federal government (through the U.S. Department of Energy [DOE]) and members of the U.S. PV industry. PVMaT is designed to accomplish this by helping the U.S. PV industry improve manufacturing processes, accelerate manufacturing cost reductions for PV modules, improve commercial product performance, and lay the groundwork for a substantial scale-up in the capacity of U.S.-based PV manufacturing plants.

The PVMaT Project is being carried out in four separate phases, designed to address separate R&D requirements. These phases are Phase 1, Phase 2A, Phase 2B, Phase 3A, and Phase 4A. A description of the focus and accomplishments for phases 1, 2A, 3A, and 2B have been detailed in previous papers {1,2,3}. Phase 3A and 2B industrial participants who are currently active have been identified in Table 1 along with subcontracts awarded under Phase 4A. A further description, by phase, of the R&D activities addressed by active PVMaT manufacturers is detailed in several papers in these proceedings.

Table 1. Current PVMaT Subcontractors

Subcontractor	Phase	Emphasis of Research	Principal Investigator
Golden Photon	2B	Commercial Scale-Up of Advanced Thin-Film Photovoltaic Technologies	Terry Brog
Solar Cells, Inc.	2B	High-Throughput Manufacturing of Thin-Film CdTe Photovoltaic Modules	Dan Sandwisch
Solarex	2B	Cast Polycrystalline Silicon PV Cell and Module Manufacturing Technology Improvements	John Wohlgemath
Springborn	3A	Development of Advanced PV Encapsulants	William Holley
Solar Design Associates, Inc.	4A1	The Development of Standardized, Low-Cost AC PV Systems	Steven Strong
Omnion Power Engineering	4A1	Three-Phase Power Conversion System for Utility Interconnected PV Applications	Hans Meyer
Utility Power Group	4A1	Development of a Low-Cost Integrated 15-kW AC Solar-Tracking Subarray for Grid-Connected PV Power System Applications	Michael Stern
Solar Electric Specialties	4A1	Design, Fabrication and Certification of Advanced Modular PV Power Systems	Glen Minyard
Trace Engin.	4A1	Modular, Bi-directional DC to AC Power Inverter Module for PV Applications	Christopher Freitas
Advanced Energy Systems	4A1	Next Generation Three-Phase Inverters	R.H. Wills
Ascension Technology	4A1	Manufacture of an AC Photovoltaic Module	Ed Kern
AstroPower.	4A2	Large Area Silicon-Film Panels and Solar Cells	James Rand
ASE Americas	4A2	Market Driven EFG Modules	Michael Kardauskas
Siemens Solar Industries	4A2	Photovoltaic Cz Silicon Module Improvements	Richard King
Iowa Thin Film Technologies	4A2	PVMaT Monolithic a-Si Modules on Continuous Polymer Substrates	Frank Jeffrey
Photovoltaic International	4A2	Manufacturing of the PVI Power Grid	Neil Kaminar

PHASE 2B

Phase 2B consisted of four 3-year subcontracts, selected from 13 proposers and awarded in late 1993. These subcontracts addressed process-specific module manufacturing problems of individual manufacturers. They included work in CdTe module manufacturing, the manufacture of Spheral Solar™ cells and modules, as well as cast polysilicon wafers, cells, and module manufacturing. These subcontracts represented new technological additions to the PVMaT Project, and were cost-shared at 58% by the subcontractors. Three of these four subcontracts (Table 1) are currently active.

PHASE 3A

Phase 3A consisted of two subcontracts, selected from 7 proposers and awarded in January of 1993. These subcontracts focused on module-related R&D problems that are common to several PV manufacturing groups. The Springborn subcontract is completing field tests in early 1997.

PHASE 4A

Phase 4A, Product-Driven Manufacturing, is the most recent phase of the PVMaT project. This is a broader approach at addressing the overall PVMaT goal of improved U.S. market share by meeting the market challenges. The solicitation included responses from individual or teamed U.S. PV and related industries addressing manufacturing of PV end-products, as well as sub-elements of these products. Objectives include: stimulating a broader interest in the production of PV products; encouraging and supporting risk-taking by industry to explore new manufacturing options and ideas for improved PV products or components; encouraging system and product integration; and stimulating advances in balance-of-systems or developments in design leading to overall reduced system life-cycle costs of the PV end-product. Cost reduction, improved efficiency, and manufacturing flexibility and broader market applications for PV systems as a whole are emphasized. The subcontracts in Phase 4A were divided into two parts, 4A1 and 4A2, and both are now completing their first year.

PHASE 4A1

Phase 4A1 addresses the product driven system and component technology and includes manufacturing improvements directed toward innovative, low-cost, high-return, high-impact PV products. Proposals in this phase addressed manufacturing that was generally related to PV system components and aspects other than modules, system components such as inverters, and/or system integration efficiency and/or design improvements, with lesser focus on module manufacturing. In addition, proposals looked at issues in system/component integration to bring all elements together for a PV product that is offered on the market. Eight two-year subcontracts (listed in Table 3) were awarded from 31 proposals received. These subcontracts are cost-shared at 25% by the subcontractors.

PHASE 4A2

Phase 4A2 is focused on product-driven PV module manufacturing Technology. Subcontracts under this phase are directing their efforts at manufacturing flexibility and module manufacturing cost reduction for a wider range of PV products. Phase 4A2 consists of five three-year subcontracts (shown in Table 4), selected from 31 proposals. These subcontracted efforts include development of large area silicon-film panel and cell manufacturing; EFG module manufacturing; improvements in CZ silicon modules; development of monolithic a-Si modules on continuous polymer substrates; and manufacturing of extruded concentrator modules. These subcontracts are cost-shared at 42% by the subcontractors.

PROGRESS IN COST REDUCTION AND CAPACITY INCREASES

At the beginning of Phase 2A subcontracted research, information was collected to establish both the current and projected capacities and module costs for the eight participating manufacturers. The results, shown in Fig. 1, represented both the diverse status of a still-maturing industry and the optimistic speculation of its members regarding the effects that the PVMaT project would have after their research efforts were allowed to take effect. Additional information was collected from the twelve PV industrial participants that were in production in late 1996.

This most recent data, shown in Fig. 2, represents an update of previous projections regarding these subcontracted efforts [4]. Data in this figure are based on each manufacturer's maximum production capacity during a given year, assuming they were to operate at maximum capacity. The average represents the average cost per watt of modules (weighted by each participant's capacity) produced by these twelve PVMaT industrial participants. Module cost estimates were then based on these manufacturing levels and included only those costs directly associated with the manufacturing of the modules (not marketing, administration, sales, etc.). It should be noted that data associated with any particular point in time, represent a potential capability. Actual manufacturing production levels may be less (and concomitant costs

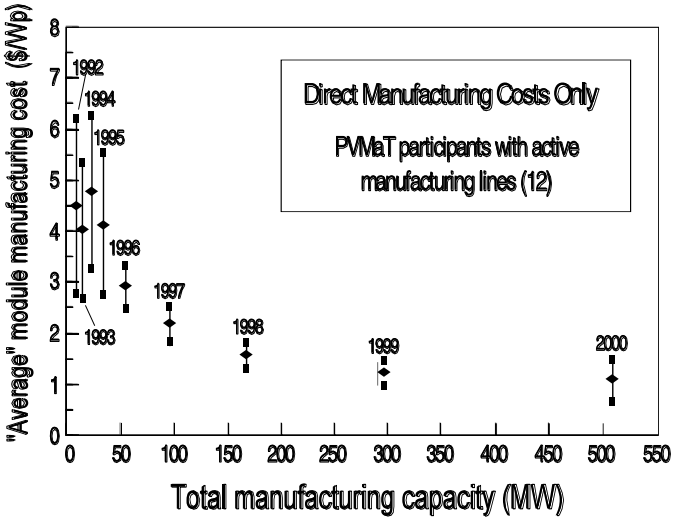

Figure 2 - PVMaT Manufacturing Cost/Capacity

higher) due to other considerations such as market conditions, available labor, etc. Figure 2 indicates that PV manufacturing capacity has increased by more than a factor of 4 in the last 4 years. Additionally, the "average" cost for manufacturing PV modules has been reduced by about 36%.

Additionally, changes were observed in projections for both "average" module manufacturing costs and manufacturing capacity. An evaluation of these 1996 modifications to the projections of 1995 and earlier demonstrate several trends among the PVMaT manufacturing participants.

The data collected in 1996 showed a 7% increase over the data collected in 1995 for the 1996 projected "average" module manufacturing costs and a 33% reduction in the projected 1996 manufacturing capacity. The increased cost adjustment resulted from; seven manufacturers increasing their module manufacturing costs from a range of 4% - 58%, and one decreasing its by 41%. The 1996 decreased capacity adjustment resulted from; one manufacturer increasing its manufacturing capacity by 3%, and five decreasing theirs in the range of 10% - 80%. The driving factors in these adjustments were: a few manufacturers pushing off their time tables for scale-up to the year-2000 levels; one manufacturer projecting a conversion of a product line to new product; and a significant reduction in the year 2000 capacity plan for another manufacturer.

Projections for 1998 also were revised, with "average" module manufacturing costs showing a 4% decrease over 1995 data and 1998 manufacturing capacity reflecting a 24% reduction. The decrease in 1998 projected costs resulted from three increasing their module manufacturing costs from a range of 14% - 42%, and three others decreasing theirs in the range of 2% - 40%. The decrease in 1998 projected capacity resulted from two increasing their manufacturing capacity in the range of 7% - 94%, and four decreasing theirs in the range of 23% - 50%. The driving factors in these adjustments were still modified time tables for scale-up to the year-2000, conversion of a product line to new product; and a reduction in planned year 2000 capacity.

Projections for 2000 "average" module manufacturing costs showed a 5% increase over 1995 data and projected 1998 manufacturing capacity reflected a 4% reduction. The increased 1998 projected costs reflect two manufacturers increasing their module manufacturing costs from a range of 11% - 46%, and four decreasing theirs in the range of 2% - 15%. The decrease in 1998 projected capacity resulted from two manufacturers increasing their capacity projections in the range of 30% - 300%, and four decreasing theirs in the range of 23% - 67%.

PVMaT participants reporting reductions in the "average" module manufacturing cost projections attributed the adjustments to better-than-expected improvements in module design, decreased materials and labor requirements, improved performance, and improved yields. The dominating factors in cost increases were identified as increased raw material costs, and more realistic estimates by the subcontractors in their actual manufacturing costs.

Manufacturers reporting reductions in their projected manufacturing capacity attributed these toseveral factors: 1) changing market conditions, 2) their having to devote unplanned time to solving product performance issues, 3) changes in business plans aimed at a more sustainable growth rate, and 4) problems with increasing materials costs. Increased projections in capacity were attributed to previously unforeseen market opportunities that have been larger and more promising than anticipated.

CONCLUSIONS

The PVMaT Project is currently finishing the first year of subcontracts under Phase 4A1 and 4A2, with research in Phase 2B concluding their third year and Phase 3A now being completed. At this time, it is apparent from Figs. 1 and 2, that the U.S. PV industry involved in the PVMaT Project has made significant progress toward reducing manufacturing costs and increasing PV module manufacturing capacity. "Average" module manufacturing costs have been reduced 36% and total manufacturing capacity for 12 PVMaT industrial participants with active lines has increased by factor of more than 4. By 1998, projections are for a reduction in the costs of 65% at $1.64/Wp, and a factor of 14 increase in capacity by 1998 to 223MW. It has also indicated in both the industries future cost/capacity data and its technical projections that its optimism for continuing these improvements is high.

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REFERENCES

[1] Witt, C.E.; Herwig, L.O.; Mitchell, R.; and Money, G.D., "Status of the Photovoltaic Manufacturing Technology (PVMaT) Project" in *Proceedings of the 22nd IEEE Photovoltaics Specialists Conference*, Las Vegas, Nevada, October, 1991.

[2] Witt, C.E.; Mitchell, R.; Mooney, G.D.; Herwig, L.O.; Hasti, D.; and Sellers, R., "Progress in Phases 2 and 3 of the Photovoltaic Manufacturing Technology Project (PVMaT)." in *Proceedings of the 23rd IEEE Photovoltaics Specialists Conference*, Louisville, Kentucky, May, 1993,.

[3] Witt, C.E. Thomas, H.P., Herwig, L.O., Mitchell, R.L.; Ruby, D.S., and Aldrich, C.C., "Recent Progress in the Photovoltaic Manufacturing Technology Project (PVMaT)" in *Proceedings of the 1st World Conference on Photovoltaics*, Waikoloa, Hawaii, December, 1994.

[4] Mitchell, R.L.; Witt, C.E. Thomas, H.P., Herwig, L.O.,Ruby, D.S., and Aldrich, C.C., "Benefits from the U.S. Photovoltaic Manufacturing Technology Project" in *Proceedings of the 25th IEEE Photovoltaics Specialists Conference*, Washington, D.C., May, 1996.